Using Cereal Grain Permittivity for Sensing Moisture Content

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***Abstract*—A brief history of cereal grain moisture measurement by sensing the electrical properties of grain is presented. The basic principles are also described for using radio-frequency (RF) and microwave dielectric properties, or permittivity, of grain for sensing moisture through their correlation with moisture content. The development of density-independent functions of the permittivity is explained. The findings of recent research are summarized, which indicate that reliable density-independent moisture content determinations can be realized by measurements on grain at RF and microwave frequencies. Development of these techniques will provide useful instruments for on-line monitoring of moisture content in flowing grain to manage moisture in grain, prevent spoilage in storage and transport, improve processing, and provide information important for yield determinations in precision agriculture applications.**

***Index Terms*—Cereal grains, density, dielectric constant, loss factor, microwaves, moisture measurement, permittivity.**

I. Introduction

MOISTURE CONTENT of cereal grains is one of the most important characteristics for determining quality. It is important in determining the proper time for harvest and the potential for safe storage. It is also an important factor in determining the market price, because the dry matter of grain has more value than the water it contains and because costs of drying for safe storage must be taken into account. In the processing of grain for flour and other food products and for animal feeds, moisture content of the materials is important information for efficient processing, achieving desired behavior of the materials, and in obtaining desired high-quality products.

Standard methods for determining moisture in grain require oven drying for specific time periods at specified temperatures by prescribed methods. Because such methods are tedious and time-consuming, they are not suitable for general use in the grain trade, and other rapid testing methods have been developed. Most of the modern practical grain moisture testers work on the principle of sensing electrical characteristics of the grain, which are highly correlated with moisture content.

Early in the 20th century, studies showed that the electrical resistance of grain was correlated with moisture content. These results and subsequent development of practical grain moisture testing instruments have been reviewed previously [1]. Instruments using the correlation between the radio–frequency (RF) dielectric properties of grain and its moisture content have been in common use at grain elevators and grading stations for more than 50 years. Such instruments were developed without detailed knowledge of the grain permittivity or dielectric properties, but circuits were developed that were influenced by the permittivity of the grain samples, and the instruments were calibrated against standard oven moisture determinations. The first quantitative data on the permittivities of grain were reported more than 45 years ago in the 1–50 MHz frequency range [2], [3]. Techniques were later developed for dielectric properties measurements on grain samples at both lower and higher frequencies [4]. Data on the dielectric properties of grain at microwave frequencies were first reported more than 25 years ago. Models were developed for several kinds of grain and soybeans covering wide frequency ranges [5], [6]. More recently, additional data on the dielectric properties of grain as a function of moisture content and temperature have become available [7]–[9].

The complex permittivity relative to free space, or complex dielectric constant, $\epsilon = \epsilon' - j\epsilon''$, where ϵ' is the dielectric constant, and ϵ'' is the dielectric loss factor, is commonly used to characterize materials. Permittivity values usually depend on frequency and temperature as well as the structure and chemical composition of materials. In grain, and other hygroscopic materials, both ϵ' and ϵ'' are highly correlated with moisture content, and this correlation has been demonstrated over very wide ranges of frequency, as shown in Fig. 1 [10]. With cereal grains and other particulate materials, permittivity is also a function of the bulk density and temperature as well. Dependence of the permittivity of rice on moisture content is shown in Fig. 2, where a linear relationship between the dielectric constant and moisture content is well illustrated.

In sensing the permittivity of static grain samples for estimation of moisture content, the dependence of permittivity on temperature and density can be determined and taken into account. However, for dynamic measurements, or on-line moisture monitoring of flowing grain, bulk density correction is much more difficult to determine.

It was recognized more than 20 years ago that microwave measurements had the capability of providing a moisture measurement independent of bulk density [12], [13]. Efforts on measuring moisture content through microwave measurement techniques were cited in previous reviews [4], [14]. It is the purpose of this paper to discuss recent findings with applicability to the sensing of grain moisture content for on-line monitoring to provide the necessary real-time moisture information.

Manuscript received May 26, 1999; revised February 28, 2000.

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Publisher Item Identifier S 0018-9456(00)04533-2.

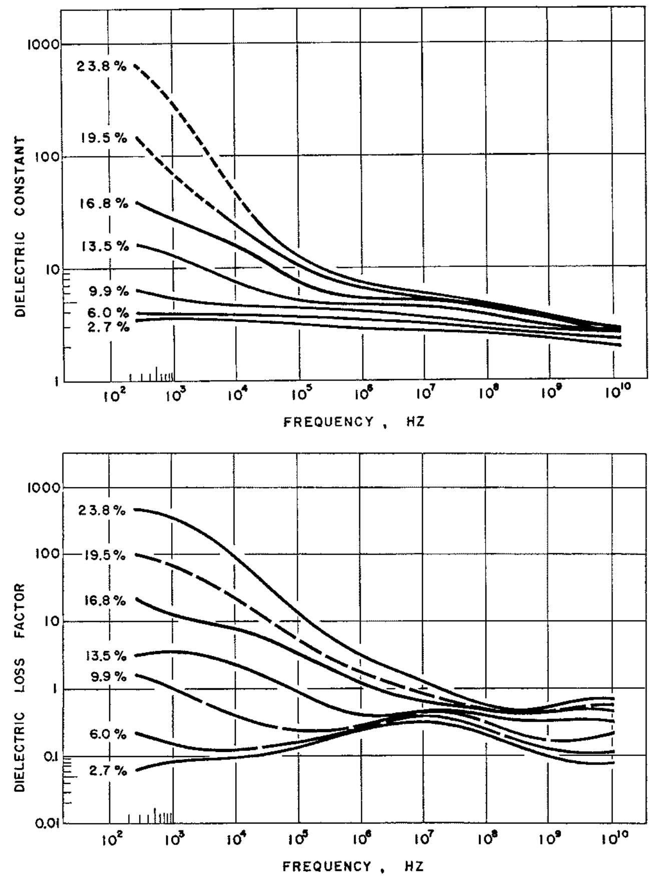

Fig. 1. Variation of the dielectric constant and loss factor of hard red winter wheat, *Triticum aestivum* L., at 24 °C, with frequency and moisture content for the range from 2.7% to 23.8%, wet basis [10].

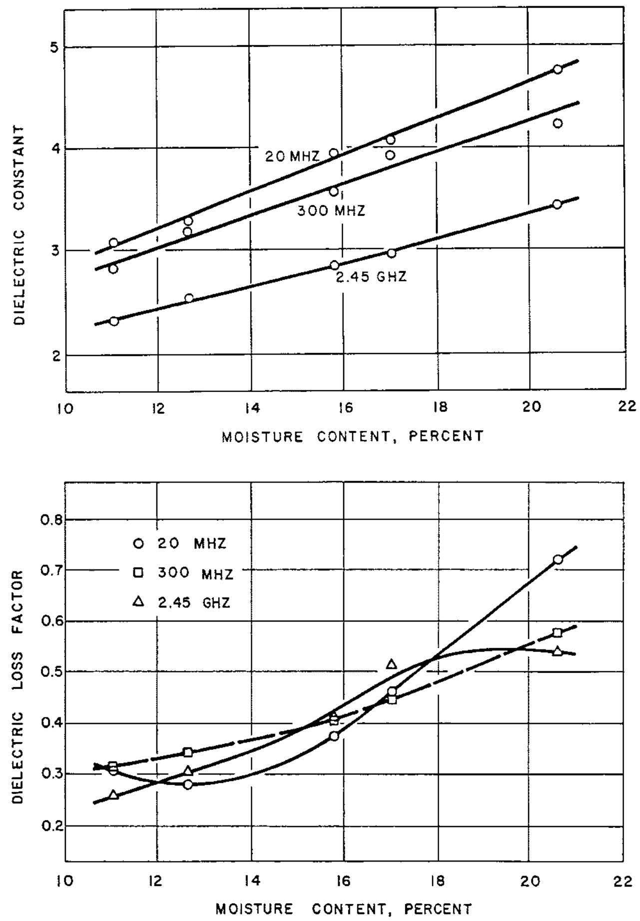

Fig. 2. Variation of the dielectric constant and loss factor of rough rice, *Oryza sativa* L., at 24 °C, with moisture content for frequencies of 20 MHz, 300 MHz, and 2.45 GHz [11].

II. Basic Principles

Because the dielectric constant of grains is so well correlated with moisture content, many electronic moisture meters have been designed with a parallel-plate or coaxial line sample holder for which the capacitance changes when a sample of grain is placed into the sample holder. The change in capacitance is directly related to the dielectric constant of the grain, and can therefore provide moisture content. Most of the RF dielectric-type moisture meters use frequencies in the range between about 1 and 20 MHz. Some use circuits that depend not only on the real part of the impedance or admittance, but also are affected by the imaginary component, which is related to the loss factor of the material. These moisture meters use a correction for temperature and for variations in bulk density or test weight of the grain. Some instruments sense temperature and weight of the grain sample and automatically correct the moisture reading for these variables, providing moisture content estimates that are satisfactory for practical use. A recent review provides more information on grain moisture sensing at frequencies below 1 GHz for practical applications [15].

Recent studies aimed at development of principles for sensing moisture content at frequencies below the microwave range have utilized capabilities for multiple frequency measurements of the complex permittivity, or complex quantities related to permittivity, to provide the additional information needed for reliable moisture sensing. Both coaxial-line and parallel-plate sample holders have been studied for eventual application to flowing grain, and, through use of spectral data analysis techniques, relatively density-independent moisture content measurements have been achieved [16]–[18].

At microwave frequencies, measurements of attenuation and phase shift obtained from transmission measurements have been used. For a plane wave of normal incidence traversing a layer of low-loss material, the components of the relative complex permittivity can be obtained as follows:

$$\epsilon' \approx \left(1 + \frac{\Phi\lambda_0}{360t}\right)^2 \tag{1}$$

$$\epsilon'' \approx \frac{A\lambda_0\sqrt{\epsilon'}}{8.686\pi t} \tag{2}$$

where

- λ_0 free-space wavelength;
- Φ phase shift in degrees;
- A attenuation in dB experienced by the wave in traversing the layer of thickness t.

Thus, in addition to the frequency used, which determines λ_0, and the layer of thickness t, the measured values of attenuation and phase shift are required to characterize the material permittivity.

Both A and Φ have been shown to be relatively linear with moisture content M in experimental measurements on several kinds of grain [19]. When they are normalized for bulk density, ρ, of the grain, the linearity still holds. Thus

$$A/(\rho t) = aM + b \tag{3}$$

$$\Phi/(\rho t) = cM + d \tag{4}$$

where a, b, c, and d are constants for a particular type of grain to be determined from regression calculations on experimental data. It follows from (3) and (4), by combination, that both moisture content and bulk density can be obtained from simultaneous measurement of attenuation and phase shift, providing the following density-independent calibration equation for moisture content and an equation for bulk density

$$M = (dA - b\Phi)/(a\Phi - cA) \tag{5}$$

$$\rho = (a\Phi - cA)/[t(ad - bc)]. \tag{6}$$

It may be noted that moisture content is provided independent of bulk density by (5), and if necessary, (6) also provides a value for bulk density at the time of the measurement. Although, in this example, $A/(\rho t)$ and $\Phi/(\rho t)$ are linear functions of moisture content, linearity is not required; only a defined function is necessary to permit the separation of the expressions for moisture content and density [19].

III. Density-Independent Functions

In addition to expressing A and Φ as linear functions of moisture content M, the ratio of phase shift and attenuation has been considered as a density-independent function for determining moisture content by microwave measurements. For plane-wave propagation through low-loss materials, the ratio of phase shift to attenuation [20]–[22] can be expressed as

$$\frac{\Phi}{A} = \left(\frac{\epsilon' - 1}{\epsilon''}\right)\left(\frac{2\sqrt{\epsilon'}}{\sqrt{\epsilon'} + 1}\right) \tag{7}$$

or the reciprocal ratio

$$\begin{aligned}\frac{A}{\Phi} &= \left(\frac{\epsilon''}{\epsilon' - 1}\right)\left(\frac{\sqrt{\epsilon'} + 1}{2\sqrt{\epsilon'}}\right)\\ &= \frac{\epsilon''}{2\sqrt{\epsilon'}\left(\sqrt{\epsilon'} - 1\right)} = \frac{\sqrt{\epsilon'}}{2\left(\sqrt{\epsilon'} - 1\right)}\ \tan\delta\end{aligned} \tag{8}$$

can be used.

Kraszewski [19] calculated the Φ/A ratio for a large amount of data on grain and developed mathematical expressions for the ratio as a function of moisture content. Comparing results for

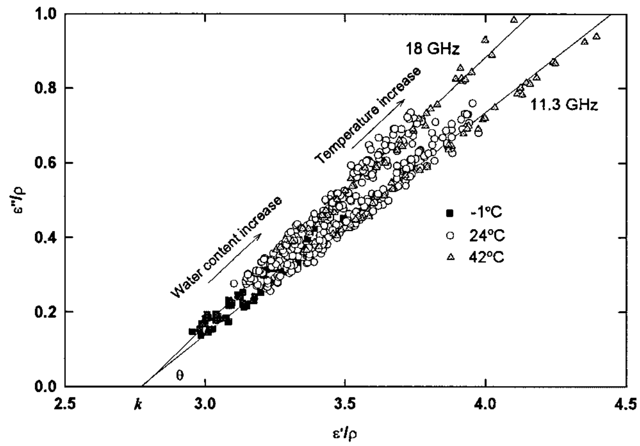

Fig. 3. Complex-plane plot of the dielectric constant and loss factor, normalized to bulk density, of hard red winter wheat samples of various moisture contents and bulk densities at indicated temperatures for two frequencies, 11.3 GHz and 18.0 GHz [26], [28].

moisture determination by this procedure to those determined with (5), the Φ/A ratio was only slightly less effective, with a standard error of performance of 0.22% moisture content compared to 0.17% for the procedure based on (5).

The first term of the right-hand side of (7), $(\epsilon' - 1)/\epsilon''$, had earlier been tested as a density-independent function in calibration equations for microwave measurement of moisture content of a number of particulate dielectrics [23], [24], since their calculations showed that the second term had little significance for low-permittivity materials. However, work by Kress-Rogers and Kent [25] on food powders revealed that this term was important.

A new density-independent function was recently reported by Trabelsi *et al.* [26]–[28]. This contribution was based on an observation of the complex-plane plot of ϵ''/ρ versus ϵ'/ρ for a large data set of measurements on hard red winter wheat at several frequencies, moisture contents, temperatures, and bulk densities. It was noted that for permittivity determinations from attenuation and phase measurements at a given frequency, all of the points fell along a straight line and that differences in either moisture content or temperature amounted to translations along that same line (Fig. 3). The lines for each frequency intersected the $\epsilon''/\rho = 0$ axis at a common point, $\epsilon'/\rho = k$, which represents the value of ϵ'/ρ for 0% moisture content or the value at very low temperature. Any change in frequency amounted to a rotation of the straight line about that intersection point. Thus, for a given frequency, the equation of the line was expressed as

$$\epsilon''/\rho = a_f(\epsilon'/\rho - k) \tag{9}$$

where a_f is the slope at a given frequency. The slope a_f varied linearly with frequency. Considering that $\tan\delta = \epsilon''/\epsilon'$ expresses the distribution between dissipated and stored energy in a dielectric, and that $\tan\delta$ varies with bulk density, it was normalized to bulk density. Solving (9) for ρ and using the resulting expression for ρ, we then have

$$\frac{\tan\delta}{\rho} = ka_f\left(\frac{\epsilon''}{\epsilon'(a_f\epsilon' - \epsilon'')}\right). \tag{10}$$

For a given frequency and particular kind of material, ka_f is a constant, and a new density-independent function can be defined as follows:

$$\xi = \frac{\epsilon''}{\epsilon'(a_f\epsilon' - \epsilon'')}. \tag{11}$$

IV. Recent Findings

In studies of swept-frequency measurements using three frequencies in the 1–150 MHz range to obtain density-independent moisture determinations, standard errors of performance of about 0.3% moisture content were achieved with wheat and corn [17], [18].

Recent microwave measurements for sensing moisture content in hard red winter wheat and hard red spring wheat at 9.4 GHz and 4.8 GHz [29] and in shelled field corn at 9.4 GHz [30], in which attenuation and phase shift were expressed as linear functions of the partial densities of water and dry matter in the grain, achieved standard errors of performance less than 0.3% moisture content for wheat and for corn. Wheat measurement data at 9.4 GHz, analyzed in terms of the Φ/A ratio, showed results that were just as good as those obtained by the other procedures. Estimates of bulk density, however, are not provided by the Φ/A ratio, whereas they are with the equations for A and Φ and with the relationship of (9).

Physical principles of moisture determination in grain by microwave measurements have been presented in more detail recently [31]. The partial densities of water and dry material in grain were expressed as functions of A, Φ, and T, the grain temperature. Moisture content and bulk density were then expressed as linear functions of these same three measured variables. Calibration equations for M and ρ were illustrated with measurement data for wheat over a range of moisture contents and temperatures. The linear model successfully provided moisture content independent of bulk density and compensated for temperature. More complicated nonlinear models were also evaluated. Values for bulk density were provided by the same measurements. General calibration equations were also considered, based on measurements at two different frequencies, which also provides a method for resolving phase ambiguity problems encountered in microwave transmission measurements [32].

The three density independent functions, Φ/A, $(\epsilon' - 1)/\epsilon''$, and ξ [equation (11)], were recently compared with an extensive set of data obtained from attenuation and phase shift measurements on static samples of hard red winter wheat at seven frequencies from 11.3 GHz to 18 GHz, three bulk density levels ranging from loosely packed to compacted, moisture contents from 10.6% to 19.2%, wet basis, and several temperatures from $-1°$C to 42 °C [27]. Results of the comparison showed that all three functions provide moisture contents independent of bulk density with standard errors of performance of 0.3% moisture content or less throughout the frequency and moisture ranges explored. Additional density-independent functions have also been considered [34].

The Φ/A function can be utilized only with transmission measurements and without the need for determining the permittivity values. However, the other two density-independent functions, which require the computation of permittivity, can be used with transmission or any other type of measurement from which permittivity values can be determined, including reflection measurements.

Development of instruments based on these principles and providing reliable instantaneous moisture content information would be extremely helpful in various processing applications [35], for yield monitoring on harvesting equipment used in precision agriculture, and for safe handling, storage, and transport of grain.

V. Conclusions

1) Permittivities of cereal grains at RF's are useful in rapid and nondestructive sensing of moisture content because of high correlations between the dielectric properties of grain and the amount of water present in the grain that exist at any frequency.
2) In addition to their dependence on moisture content, the dielectric properties of grain are dependent on the frequency, and upon the temperature and the bulk density of the granular materials. These variables must be taken into account for reliable moisture content sensing.
3) At RF's below the microwave region, between 1 MHz and 350 MHz, density-independent moisture content determination is achievable with multiple-frequency measurements and spectral and statistical data analysis.
4) At microwave frequencies, density-independent moisture sensing has been achieved by single-frequency measurements of attenuation and phase shift or by the use of density-independent functions of the dielectric constant and loss factor. These values may be obtained by any means, including transmission or reflection measurements.
5) The techniques of density-independent moisture sensing by RF and microwave measurements offer promise for development of instruments for practical use in monitoring moisture content of grain and other materials on-line for process control and management.

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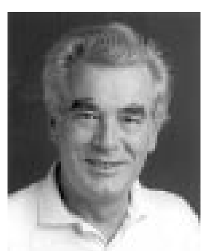

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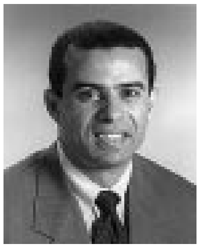

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